Description of accretion induced outflows from ultra-luminous sources to under-luminous AGNs

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Abstract

We study the energetics of the accretion-induced outflow and then plausible jet around black holes/compact objects using a newly developed disc-outflow coupled model. Inter-connecting dynamics of outflow and accretion essentially upholds the conservation laws. The energetics depend strongly on the viscosity parameter α and the cooling factor f which exhibit several interesting features. The bolometric luminosities of ultra-luminous X-ray binaries (e.g. SS433) and family of highly luminous AGNs and quasars can be reproduced by the model under the super-Eddington accretion flows. Under appropriate conditions, low-luminous AGNs (e.g. Sagittarius A^*) also fit reasonably well with the luminosity corresponding to a sub-Eddington accretion flow with $f \to 1$.

keywords: accretion, accretion disc — black hole physics — X-rays: binaries — galaxies: jets — galaxies: nuclei

1 Introduction

Extremely high resolution observations of the powerful extragalactic double radio sources [Blandford & Rees 1974, Begelman, Blandford & Rees 1984, Ferrari 1998, Mirabel 2003] reveal that they are formed by well-collimated outflows or jets that continuously emerge from the nuclear region of the host active galaxies (AGNs) or quasars, believed to harbor supermassive black holes. Similarly micro-quasars [Mirabel & Rodriguez 1994, Mirabel & Rodriguez 1998] discovered in recent times reveal that outflows are generated from stellar mass black holes (or black holes candidates). The well-collimated outflow in SS433 observed for several decades, which is our galactic, persistent, super-critical accretor, is an well known evidence of cosmic jet [Margon 1984]. Further, highly collimated line jets are seen in young stellar objects [Mundt 1985]. Relativistic jets are also observed in neutron star low mass X-ray binaries (LMXBs) [Migliari & Fender 2006].

The outflows/jets extract matter, energy and momentum from the accretion disc that forms around the compact object, and thus the dynamics of outflow leading to jet is intrinsically coupled with the accretion dynamics through the conservation laws. Also several observations (precisely the simultaneous observations of disc and jet; see e.g. Ghosh & Mukhopadhyay 2009, and references therein) reveal that accretion processes and outflows are strongly correlated and they eventually control the accretion process, precisely, the accretion dynamics in the vicinity of the central star. The relativistic outflowing matter, in the case of quasars or micro-quasars, should indeed come only from the inner region of the accretion disc. This is particularly suggestive as the quasars or the micro-quasars do not have an atmosphere of their own. However, most of the models of accretion disc and outflow/jet have been evolved separately, considering these two to be apparently dissimilar objects. The outflow/jet models have been evolved over the years, from speculative ideas such as de Laval nozzles [Blandford & Rees 1974] to electrodynamic acceleration model [Blandford & Znajek 1977], centrifugally driven outflows [Blandford & Payne 1982, Pudritz & Norman 1986], etc. Moreover, MHD simulations of outflow/jet have been performed both in non-relativistic as well as relativistic limits, mostly in the Keplerian paradigm (e.g. Hawley & Balbus 2002, Mizuno et al. 2006, Hawley & Krolik 2006, and references therein) to see how the matter gets deflected from the equatorial plane. Nevertheless, the definitive understanding of the origin of outflows/jets is sill unknown.

The radiatively driven outflow or jet whose origin is better understood, can be envisaged when the accretion disc is highly radiation pressure dominated or

precisely “radiation trapped”. This is likely to occur when the accretion rate is super-Eddington or super-critical [Lovelace et al. 1994, Begelman et al. 2006, Fabrika 2004, Ghosh & Mukhopadhyay 2009] as in ultra luminous X-ray (ULX) sources such as SS433 (with luminosity $\sim 10^{40}$ erg/s or so) [Fabrika 2004]; a prototype of ULXs in external galaxies having relativistic jets. The super-critical flows are optically thick and have a strong advective component [Lipunova 1999, Ohsuga et al. 2005]. The unusual signatures of ULXs, compared to their counterparts, lie in their extreme high luminosity ($L_{bol} \sim 10^{39-41}$ erg/s), strong spectral variability and their association with the actively star forming regions, that make their nature a subject of controversy [Fabrika 2004, Mushotzky 2004]. Recently, an ultra-luminous accretion disc with a high kinetic luminosity radio jet has been discovered in quasar PKS 0743-67 [Punsly & Tingay 2005], which indicates that the ultra-luminous sources may be extended to quasars or even AGNs. On the other extreme end, the under-luminous AGNs and quasars (e.g. Sagittarius A^*) had been described by the advection dominated accretion flow model (in short ADAF [Narayan & Yi 1994]), where the flow is substantially sub-critical/sub-Eddington. The model hypothesized a plausible emergence of strong outflows/jets, which lead to reveal a strong inter-connection between the outflow and advection.

Very few models exist which simultaneously deal with the accretion and outflow/jet dynamics on the same platform, both in analytical regime as well as through numerical simulations (see Ghosh & Mukhopadhyay 2009, and references therein). The difficulty of simultaneous simulation of the disc and outflow arises due to the difference in time scales between accretion and outflow. Also the results strongly depend on the initial conditions [Ustyugova et al. 1999]. The 2.5-dimensional disc-outflow coupled model given by Ghosh & Mukhopadhyay (2009) has been formulated by incorporating explicit information of the outflow in a fully analytical regime through a self-similar approach in a general advective paradigm, by upholding the conservation laws. It has been further shown that with mass, energy and momentum conservation, and a few scaling arguments, the correlation of the jet with the disc could be successfully modeled. The authors solved a complete set of partial differential fluid equations (with the variation of flow parameters in both radial and vertical direction) without assuming the vertical hydrostatic equilibrium, with the explicit inclusion of the vertical velocity (representing outflow) and all the relevant components of the stress tensor apart from the usual $W_{r\phi}$, from the first principle. They used their solutions to study two extreme cases of the geometrically thick advective accretion flows: super-critical and high sub-critical, which are more probable regimes of the strong outflows and jets. They found that the flow parameters of the accretion-induced outflow/jet strongly

depend on Shakura & Sunyaev viscosity parameter α [Shakura & Sunyaev 1973] and cooling factor f.

In the present paper, we use and extend the above mentioned work [Ghosh & Mukhopadhyay 2009] to study the detailed energetics of the accretion-induced outflow and then plausible jet. In order to do that, we stick to two extreme regimes of the black hole accretion: super-critical and high sub-critical, to describe ultra/highly luminous and under-luminous sources respectively. For obvious reasons, we do not repeat the calculation and the formulation of the disc-outflow model given earlier [Ghosh & Mukhopadhyay 2009], but will recall them appropriately.

We arrange the paper in the following manner. In the next section, we formulate the equations for the energetics of the accretion-induced outflow. In §3, we study the properties of the disc-outflow energetics. Finally we end in §4 with a discussion and implications.

2 Energetics of the accretion-induced outflow

In order to study the energetics of the outflow, we need to compute the mass outflow rate. Blandford & Begelman (1999) generalized the ADAF solution [Narayan & Yi 1994] by including wind and outflow, assuming the mass inflow rate to be proportional to r^p, where $0 \leq p < 1$ (r be the radial coordinate). Chakrabarti and his collaborators [Das & Chakrabarti 1999, Chakrabarti 1999] also attempted to calculate the mass outflow rate from a disc involving a shock without including the vertical flow explicitly. In the present paper, we derive this self-consistently. Integrating the continuity equation [Ghosh & Mukhopadhyay 2009] vertically about the equatorial plane we obtain

$$\frac{d}{dr}\int_{h_0}^{h} 4\pi r\rho v_r \, dz \; + \; 4\pi r(\rho(h)v_z(h) - \rho(h_0)v_z(h_0)) = 0, \tag{1}$$

where v_r and v_z are the radial and the vertical velocity respectively, $h(r)$ is an arbitrary disc scale height and h_0 the minimum (finite) height of the disc-outflow system, which is different for super-Eddington and sub-Eddington accretion flows, z be the vertical coordinate. Here we deliberately focus on the disc-coronal region (sub-Keplerian halo), from where the mass loss takes place in the form of wind or outflow, and hence the solution at equatorial plane looses significance. The integral in the first term of the left-hand side of eqn. (1) represents the disc mass

accretion rate given by

$$\dot{M}_a(r) = -\int_{h_0}^{h} 4\pi r \rho v_r \, dz. \tag{2}$$

The second term then can be attributed to the rate of change of outflow (and then plausible jet) mass, given by

$$\frac{d\dot{M}_j(r)}{dr} = -4\pi r(\rho(h)v_z(h) - \rho(h_0)v_z(h_0)) = -\frac{d\dot{M}_a(r)}{dr}. \tag{3}$$

Here, $\dot{M}_j(r)$ is analogous to the mass outflow rate represented as

$$\dot{M}_j(r) \;=\; -\int 4\pi r(\rho(h)v_z(h) - \rho(h_0)v_z(h_0))\, dr + c_j, \tag{4}$$

where the constant c_j is to be determined by an appropriate boundary condition. Thus from eqn. (3) the total mass accretion rate can be written as

$$\dot{M} = \dot{M}_a(r) \;+\; \dot{M}_j(r). \tag{5}$$

Eqn. (5) entails that under the stationary condition the radial mass flux in the disc decreases as the inflowing matter approaches the central object, at the same rate at which the vertical mass flux increases to maintain a constant $\dot{M}$ which is exactly the net mass accretion rate at infinity.

To compute the power of the outflow and then plausible jet, following previous work [Ghosh & Mukhopadhyay 2009], we integrate the disc-energy conservation equation for an accretion-induced outflow over the disc scale height which yields

$$\frac{d}{dr}\int_{h_0}^{h} 4\pi r \mathcal{F}_r \, dz \;+\; 4\pi r(\mathcal{F}_z(h) - \mathcal{F}_z(h_0)) \;=\; 0. \tag{6}$$

Here, $\mathcal{F}_z$ is the vertical component of the total energy flux given by

$$\mathcal{F}_z = \left(\frac{v^2}{2} + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} + \phi_G\right)\rho v_z - v_\phi W_{\phi z} + F_z, \tag{7}$$

where $v^2 \;=\; v_r^2 + v_\phi^2 + v_z^2$, ϕ_G is the gravitational potential, F_z the radiative flux from the disc surface, $W_{\phi z}$ the ϕz^{th} component of the stress tensor, γ the ratio of the specific heats of the gas-radiation mixture. We thus obtain the power of the

outflow from eqn. (6), which is the total power removed from the disc by the outflow, as

$$P_j(r) = \int 4\pi r(\mathcal{F}_z(h) - \mathcal{F}_z(h_0))\, dr. \tag{8}$$

We then calculate the disc luminosity in presence of outflow (and jet) using disc-energy conservation equation described earlier [Ghosh & Mukhopadhyay 2009]

$$L = (1 - f) \int \left(\int_{h_0}^{h} Q^{+} 4\pi r dz \right) dr, \tag{9}$$

where Q^+ is the total viscous heat generated in the disc. We now introduce three dimensionless parameters which correlate the disc and the outflow leading to jet: $q_{jm}(r) = \dot{M}_j(r)/\dot{M}$, $q_{jp}(r) = P_j(r)/\dot{M}c^2$ and $q_l = L/\dot{M}c^2$. We do not describe here the generalized Bernoulli's number (B_E), explicitly shown earlier [Ghosh & Mukhopadhyay 2009], which represents the total energy of the system.

3 Properties of the energetics of disc and outflow

Accretion by a black hole (or any other central star) is the primary source of the mass outflow and jet formed in the inner hot region of the disc. At the first instant we neglect the contribution of magnetic field which is likely to be the origin of collimation and acceleration of jet. However, doubts can be raised about the significance of the magnetic field for production, collimation and acceleration of jets in ULXs and highly luminous AGNs and quasars, which are supercritical and highly radiation trapped systems (see Fabrika 2004, for details). We argue that the radiation pressure is likely to be the plausible reason for strong outflows and then plausible jets in high mass accretion flows [Lovelace et al. 1994]. The inflowing matter is expected to be ejected and accelerated through a funnel like region [Fukue 1987, Fabrika 2004] by the strong radiation pressure leading to strong outflow and then plausible jet from the disc. In early, based upon the geometrically thick accretion disc model, it was shown that very narrow and deep funnels are formed around the rotation axis of the accretion disc and most of the disc energy flux is radiated from the surface of the funnels. The radiation pressure may accelerate the outflowing mass in funnels up to relativistic velocities in the form of two jets pointing in opposite directions as observed in SS433 [Jaroszyński, Abramowicz & Paczyński 1980, Abramowicz & Piran 1980]. In

the inner accretion disc, a few Schwarzschild radii away from the black hole, as the infall time scale is much smaller than the viscous time scale to transport angular momentum outside, matter has no time to loose angular momentum and attains a near constant value. Around this region the centrifugal force becomes comparable to the gravitational force, and thus the incoming matter slows down at this centrifugally dominated region and gets puffed up [Chakrabarti 1999]. Therefore, a funnel type geometry is likely to form around the region and the radiation pressure blows up the matter through them.

However, the magnetic field is likely to play the role in generating turbulence in the hot disc systems [Balbus & Hawley 1991]. In fact, for critical or sub-critical accretion flows, the jet is likely to form due to the magnetic activity in the disc [Blandford & Payne 1982, Camenzind 1986]. We do not intend to discuss here the possible reason of the emanation of the jet. Whatever the explanation/mechanism be, the potential dynamics of the accretion-induced outflow and then plausible jet always upholds the conservation laws which shows several interesting features. The dimensionless parameters $q_{jm}(r)$, $q_{jp}(r)$, q_l and B_E carry the information of the disc-outflow energetics. In the next two subsections we analyse their features for super-critical and sub-critical accretion flows respectively.

3.1 Super-critical accretion

To study the high mass accretion flows, we consider $\dot{M} \sim 3 \times 10^{-4} M_\odot/yr$ corresponding to the central mass $M \sim 10 M_\odot$, which is a probable estimate of the accretion rate of our own galactic super-critical accretor SS433 [Fabrika 2004]. We express $\dot{M}$ in terms of critical Eddington unit so that, for our case, $\dot{M} \sim 10^4 \dot{M}_{cr}$. This makes the energetic profiles independent of mass of the central star and one can extend our model to the case of high or ultra-luminous AGNs and quasars. Figures 1a and 1b depict the variation of mass outflow rate and power of the outflow and then plausible jet respectively as functions of r. The nature of profiles is similar to that of vertical component of velocity v_z, explained in detail earlier [Ghosh & Mukhopadhyay 2009]. At $f = 0.4$, a substantial amount of matter and radiation is extracted in the form of strong outflow leading to jet and thus the power of the outflow is significantly high, which falls off rapidly for $f > 0.4$.

The luminosity profile (Fig. 1c) exhibits an interesting feature. At small r, it increases slowly (although not very clear from the figure that is given in the logarithmic scale) with r and eventually attains a near constant value. At high α, the luminosity corresponds to the Eddington or the super-Eddington accretion. However the system becomes sub-Eddington at low $\alpha \sim 0.01$, even

if $\dot{M} \sim 10^4 \dot{M}_{cr}$ and f low. This extreme sensitivity is due to the fact that α directly controls the viscous heat generation. At $f = 0.4$, for $\alpha \sim 0.3$, L reaches $\sim 10^{41} erg/s$, resembling highly luminous and ultra-luminous XRBs (e.g. CXOU J095550.2+694047 [Kaaret et al. 2001], GRS 1915+105, GRO J1655-40 [Mirabel & Rodriguez 1998]). At $f > 0.4$, L decreases in orders of magnitude but still lies within the range of the high or ultra-luminous regime (as in the case of SS433). For a black hole of mass $M \sim 10^6 - 10^9 M_{\odot}$, it can be shown that L attains a value $\sim 10^{46} - 10^{49}$ erg/s for $\alpha = 0.3$ and $f = 0.4$. Such luminosity is commonly observed in highly luminous AGNs and ultra-luminous quasars (e.g. PKS 074367), possibly in ULIRs [Genzel et al. 1998] and narrow-line Seyfert 1 galaxies (e.g. [Mineshige et al. 2000]). The nature of the variation of B_E has been shown in Fig. 1d,e, already explained by Ghosh & Mukhopadhyay (2009) with three-dimensional plots.

The truncation of the curves attributes to the truncation of the disc due to evaporation to corona. With the decrease of f, which corresponds to more increase of radiation pressure, the disc gets more radiation pressure dominated and the matter gets blown up due to the strong radiation pressure further out. At this situation, the disc tends to become more Keplerian and thus centrifugally dominated. Therefore the centrifugal dominated boundary layer is likely to form at a larger radius. As a result the outflow rate and then the outflow/jet power increase significantly and the disc gets truncated at a larger radius.

In Fig. 2, we show a comparison of v_z, q_{jm}, q_{jp} and q_l between two values of γ at the same set of α and f. With a small increase in the value of γ from 1.4 to 1.444, the above parameters decrease by an enormous margin. The abrupt change of the corresponding parameters reflects that the system is very sensitive to γ and then β which is the ratio of the gas pressure to total pressure [1]. An increase of γ from 1.4 to 1.444 corresponds to an increase of β from 0.3 to 0.5, which further corresponds to the conversion from radiation dominated to marginally gas dominated system. This signifies that the gas pressure in the system increases, which means that the radiation pressure of the system suddenly decreases. The decrease in the radiation pressure inhibits strong outflow [2]. Hence the power of the outflow and mass outflow rate fall in order of magnitudes. The same reasons are applicable in order to explain the variation of luminosity profiles.

[1] The relation between γ and β is given in Ghosh & Mukhopadhyay 2009.

[2] In super-critical, radiation pressure dominated regime, strong radiation pressure blows up the matter to form outflow and consequently plausible jet.

3.2 Sub-critical accretion

Here we consider that the flow has a mass accretion rate $\dot{M} \sim 10^{-2}\dot{M}_{cr}$ corresponding to $M \sim 10^6 - 10^7 M_\odot$, which renders the flow to be thick and gas pressure dominated. Figure 3 shows that the mass outflux and the power extracted from the disc by the outflow are much less compared to that of the high mass accretion flows. Even for a near extreme $f \sim 0.7$, B_E is ~ 4 times larger for super-critical flows compared to the ideal case of an advection dominated ($f \to 1$) sub-critical accretion flow. This signifies that outflows are more probable for super-Eddington accretion flows compared to that of sub-Eddington flows. For low α and $f = 0.9$, we obtain a luminosity $L \sim 10^{33} erg/s$ corresponding to $M \sim 10^6 M_\odot$ (Fig. 3c). For high $\alpha \sim 0.3$, L increases by three orders of magnitude (not shown in the figure) at the same f. Such low luminosities are observed in many under-luminous AGNs (e.g. Sagittarius A^*; [Mahadevan 1998]).

4 Discussion

Based on a 2.5 dimensional hydrodynamical formulation of a disc-outflow coupling system with a set of self-similar solutions [Ghosh & Mukhopadhyay 2009], we have studied the energetics of the system. The self-similar approach is not just a mere tool to solve the non-trivial coupled partial differential equations. The accretion flow indeed may exhibit self-similar behaviour. It was shown earlier that the black hole system GRS 1915+105 is chaotic in nature [Misra et al. 2004] that supports the idea of inner disc instability and then turbulence. It was also found that the corresponding correlation/fractal dimension to be similar to that in the Lorenz system which is a model example of an ideal chaos. The low correlation/fractal dimension implies possible self-similarity into the system. In reality the accretion flows with strong outflows are likely to be geometrically thick and advective, which more possibly occur in ultra-luminous and under-luminous accreting sources. The standard Keplerian model [Shakura & Sunyaev 1973] fails to describe these two opposite traits of observational signatures, which are possible sources of powerful outflows and jets.

The energetic profiles strongly depend on α and f. They also reveal that outflows and jets are more probable and powerful for super-Eddington accretion flows compared to the sub-critical ones, which correspond to ultra-luminous and under-luminous sources respectively. For super-Eddington flows (Fig.1), the disc gets truncated at larger radii compared to the sub-Eddington ones. This means that the

outflow/jet may occur at the inner region of the disc and the disc-corona transition region may form in the vicinity to the central star in case of sub-Eddington flows. However, a slight departure of γ from ~ 1.4 to a higher value leads to an abrupt decrease in the energetics of the flow. We have shown that at super-Eddington accretion flows ($\dot{M} \sim 10^4 \dot{M}_{cr}$), with an appropriate choice of α and f, the luminosity calculated from our model is $L \sim 10^{41}$ erg/s corresponding to a black hole of mass $M \sim 10 M_{\odot}$. Such a high luminosity is commonly observed in exotic ULXs in external galaxies or in our own super-critical accretor SS433.

With the appropriate choice of free parameters α, f, M and $\dot{M}$, we have shown that our model can reproduce the luminosities observed in ultra luminous sources and other family of high luminous AGNs (Fig. 1c), which probably accrete super-critically. Similarly, the luminosity observed in under-luminous AGNs (e.g. Sagittarius A^*) can also be reproduced by our model at $f \rightarrow 1$ (Fig. 3c). This particular situation is similar to ADAF [Narayan & Yi 1994]. The limitation of ADAF can be addressed by incorporating outflow from the disc (as of Ghosh & Mukhopadhyay 2009), which may turn the disc into a non-radiative accretion flow and thus can explain luminosity profile of under-luminous sources. As our solutions can explain the observed luminosities of both ultra-luminous sources and under-luminous AGNs with the appropriate choice of free parameters, we should put our model to more observational tests. Although we have neglected the contribution of the magnetic field, whose importance for super-critical accretion flows is probably not significant [Ghosh & Mukhopadhyay 2009], the inclusion of the magnetic field will render the system to be more realistic. Such a work will be pursued in the course of time. In the follow up work, we plan to analyse a full scale numerical solution to conform/verify the results discussed here.

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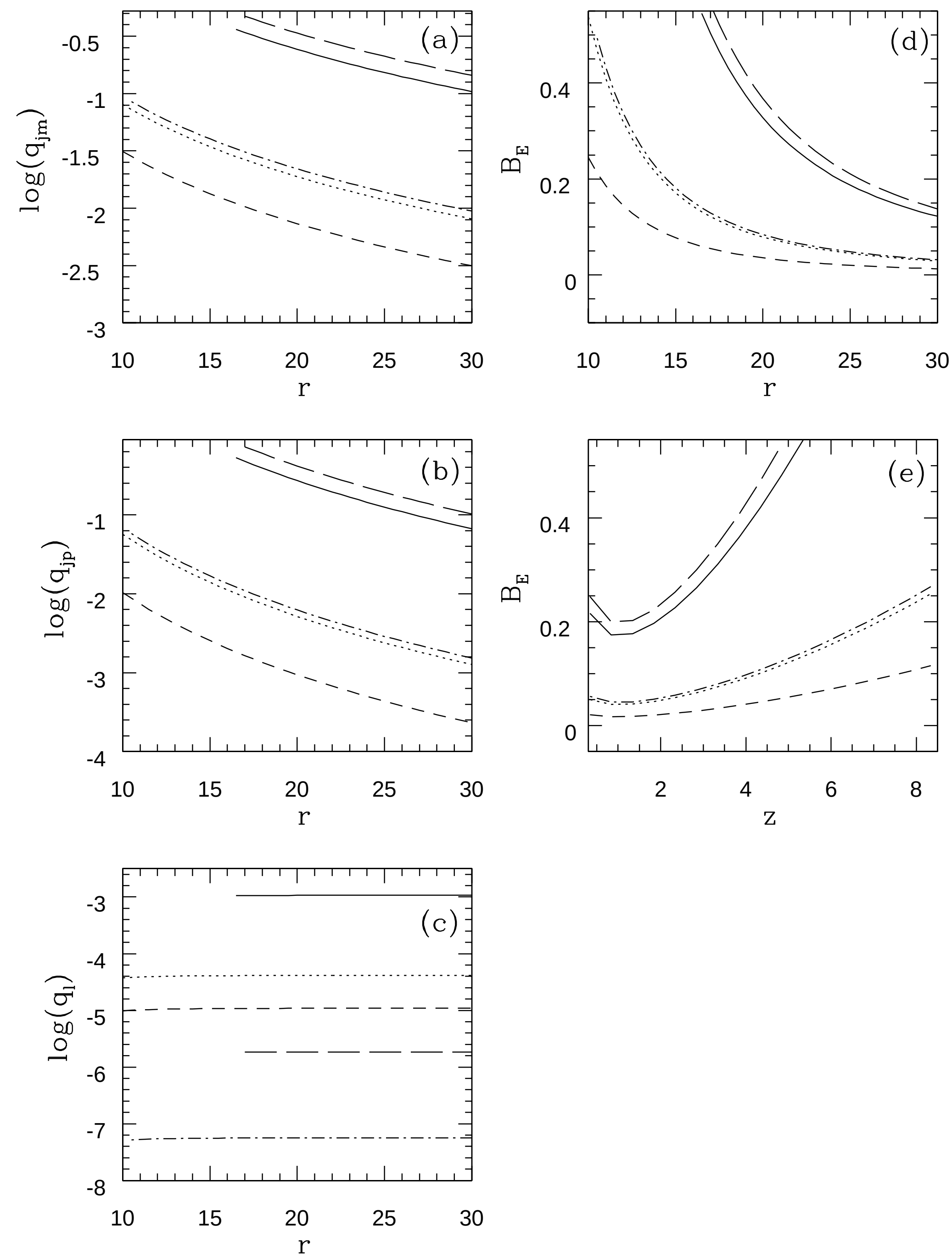

Figure 1: Variation of (a) mass outflow rate, (b) outflow/jet power, (c) luminosity in unit of $\dot{M}c^2$, (d) Bernoulli's constant, as functions of radial coordinate for super-Eddington accretion flows. (e) Variation of Bernoulli's constant as a function of z. Solid, dotted, dashed curves are for $\alpha = 0.3$ and $f = 0.4, 0.5, 0.7$ respectively. Long-dashed, dot-dashed curves represent flow with $\alpha = 0.01$ and $f = 0.4, 0.5$ respectively. Other parameters are $\gamma = 1.4$, corresponding $\beta \sim 1/3$, and $z = 5$.

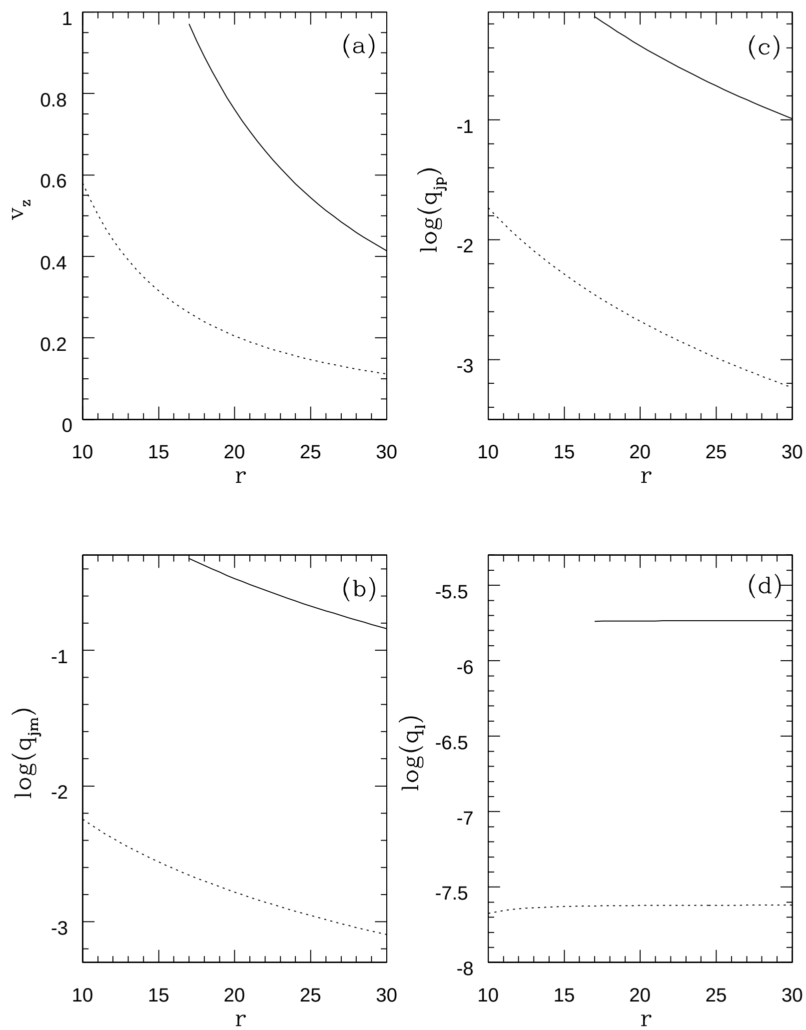

Figure 2: A comparison of various quantities between two different γ for super-Eddington accretion flows as functions of radial coordinate. Solid and dotted curves are for $\gamma = 1.4$ and $\gamma = 1.44$ respectively. Other parameters are $\alpha = 0.01$, $f = 0.4, z = 5$.

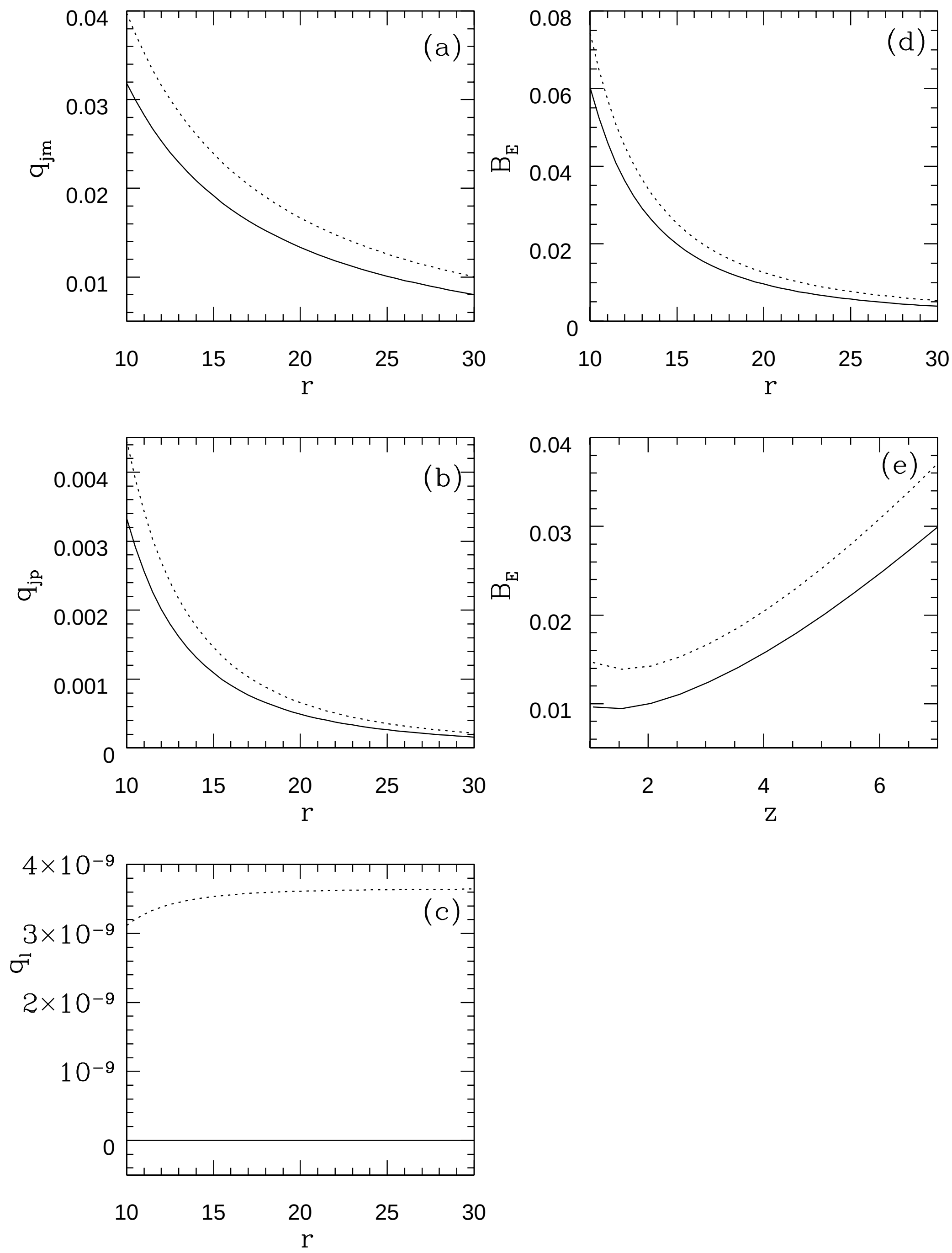

Figure 3: Same as Fig. 1, but for sub-Eddington accretion flows. Solid and dotted curves are for $\alpha = 0.3$, $f = 1$ and $\alpha = 0.01$, $f = 0.9$ respectively. Other parameters are $\gamma = 1.6$, corresponding $\beta \sim 0.89$, $z = 5$.